

API Technical Bulletin:

Migration of Soil Gas Vapors to Indoor Air:

An Empirical Assessment of Subsurface Vapor –to- Indoor Air Attenuation
Factors Using Data from the CDOT-MTL Denver, Colorado Site

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Executive Summary

The area surrounding the Colorado Department of Transportation Materials Testing Laboratory (CDOT-MTL) in Denver, CO has been subject to intense investigation in recent years. Thousands of groundwater, soil gas, and indoor air samples have been collected in order to investigate impacts associated with a release of chlorinated solvents. This extensive data set has been used in this work to: a) derive relationships between subsurface and indoor air contaminant concentrations at this site, b) compare those field data-derived results with estimates generated from the Johnson and Ettinger (1991) screening model, and c) identify key lessons-learned for assessing impacts to indoor air from subsurface contamination. The results of this study show that: a) empirically-derived attenuation factors fall in the range 10^{-6} to 10^{-4} , with an overall average of 3×10^{-5} [(mg/L-indoor air)/(mg/L-soil gas)], b) screening level predictions for reasonable inputs range from 4×10^{-6} to 2×10^{-4} with a best estimate of 9×10^{-5} [(mg/L-indoor air)/(mg/L-soil gas)] , and c) the data suggest that use of direct indoor air sampling for routine assessment of this pathway is likely to be problematic, unless large numbers of samples are collected and the data is sufficient to conclusively establish a linkage between indoor air and subsurface contamination.

1.0 Introduction

With the advent of risk-based decision-making at petroleum and other chemical-release sites, screening-level models for the subsurface vapor –to- indoor air pathway are now being used to: a) identify scenarios for which there might be significant adverse impacts, b) determine when additional assessment is necessary, and c) develop target soil and groundwater screening levels.

A range of approaches for addressing this pathway have been proposed and debated for the past decade. At the extremes are approaches relying solely on screening-level predictive models and approaches always requiring indoor air sampling. Intermediate are approaches that combine screening level models and various levels of site-specific sampling, such as the approach presented in API Publication 4674.

Historically, objective comparison of these different assessment approaches has been difficult. The available information has been limited to anecdotal observations and incomplete single-building data sets. While, this is still pretty much the case, extensive data sets are now becoming available for a few sites. One such site is the Colorado Department of Transportation Materials Testing Laboratory (CDOT-MTL) Site located in Denver Colorado. What makes this data set especially interesting is the large number (>1000) of groundwater, soil gas, and indoor air concentration data, and the fact that the multi-event sampling was conducted at a number of locations.

This technical bulletin describes an independent analysis of this data set, with emphasis on:

- empirical derivation of attenuation factors for the soil vapor –to- indoor air pathway using measured groundwater and indoor air concentrations,
- comparison of the empirically-derived attenuation factors with those estimated using the Johnson and Ettinger screening-level model and reasonable input values for this site, and
- implications of the lessons-learned for other sites in the future

This technical bulletin is organized as follows:

- Section 2.0 presents a description of the CDOT-MTL site history and characteristics, as well as a brief summary of the measurements and methods.

- Section 3.0 discusses the data quality assurance approach used in the initial review of the data.
- Section 4.0 describes the empirical development of vapor migration pathway attenuation factors using only CDOT-MTL site data.
- Section 5.0 presents a comparison of empirically-derived attenuation factors with those estimated using the Johnson and Ettinger (1991) screening-level model, and a sensitivity analysis to model inputs.
- Section 6.0 contains lessons-learned from reflection on the data from this site, with emphasis on implications for other sites.

2.0 CDOT-MTL Site Background and Measurements

The CDOT-MTL site is located in Denver, Colorado. It has functioned as a central testing laboratory for pavement materials, paints, and other transportation-related research since 1957. Documents report that chlorinated solvents were accidentally released from two on-site underground waste storage tanks installed in the early 1970's. This resulted in contamination of soils, groundwater, and soil gas.



Figure 2. Photos of the CDOT-MTL site and surrounding apartment buildings.

Figure 1 presents a plan view of the immediate area surrounding the CDOT-MTL site, while Figure 2 presents photos of the MTL site and surrounding apartment buildings. Of interest here are the multi-family apartment buildings found to the north-east, as these are found above the contaminated groundwater plume and have been the focus of intensive indoor air sampling.

Based on soil, groundwater, and soil gas analyses results, the extent of soil contamination appears to be limited to the CDOT-MTL site property and immediate vicinity. Dissolved chlorinated compounds have migrated off-site to the north-east with groundwater flow as shown in Figure 1. Chlorinated chemicals have been detected in soil gas wherever soil or groundwater contamination is present.

As mentioned above, soil, groundwater, soil gas, and indoor air sample results are available. Of interest here are the pre-remediation data collected mostly during the 1994 – 1997 time period. Groundwater concentrations are derived from chemical analyses of groundwater samples collected from approximately 60 monitoring wells, with about 10 of those wells being located in the area of interest for this work (defined roughly by the 1,1 DCE plume contours depicted in Figure 1). Indoor air concentrations come from EPA Method TO-15 analyses of 24-h average Summa canister samples. Over 1000 indoor air concentrations are available; as a result of our data quality analysis review (discussed below), we have focused mainly on the samples collected from the buildings labeled KAA, SP3, SP4, SP5, AGA, AGB, and AGE in Figure 1. Soil gas samples were collected by a combination of sampling methods; some involved the use of dedicated multi-level samplers, while others used one-time drive-point samplers.

3.0 Data Quality Analysis Approach

Prior to using any data set for the derivation of empirical relationships, it is necessary to assess its data quality. This often results in a filtering of some of the data, to ensure that the data set that is used contains only the data for which one has a high degree of confidence. Data quality analysis is especially important when dealing with the soil gas –to- indoor air pathway, because:

- It is common for non-detect vapor and groundwater concentrations to be entered in environmental databases as one-half the detection level; these values must be removed as the actual concentration in that sample is unknown (otherwise one may inadvertently end up determining relationships between non-detect levels in the subsurface and indoor air).
- It is important to establish a conclusive connection between concentrations of chemicals found in the subsurface and those found in indoor air as there is the potential for other indoor and outdoor sources of the chemicals of interest.

For this work, the data quality analysis consisted of: a) removing all non-detect values from the groundwater, indoor air, and soil gas data sets, and then b) looking for data consistency within each data set, and across data sets. The latter was accomplished via the following steps:

Step 1: Plot all groundwater concentrations relative to the 1,1 DCE groundwater concentrations to assess internal groundwater data consistency. For relatively recalcitrant compounds like these, we expect the ratios of chemical concentrations in groundwater to remain consistent across a wide range of concentrations.

Step 2: Plot all soil gas concentrations relative to the 1,1 DCE soil gas concentrations to assess internal soil gas data consistency. As in Step 1, we expect the ratios of chemical concentrations in soil gas to remain consistent across a wide range of concentrations. In addition, soil gas concentrations are plotted vs. depth to look for expected behavior; in this case we expect soil gas concentrations to increase with depth as groundwater is the source of contaminant vapors in the region of interest.

Step 3: Plot all indoor air concentrations relative to the 1,1 DCE indoor air concentrations to assess internal consistency. As in Steps 1 and 2, we expect the ratios of chemical concentrations to remain consistent across a wide range of concentrations.

Step 4: Compare the quantitative relationships observed between the relative concentration ratios (e.g., TCE/1,1 DCE) in groundwater, soil gas, and indoor air. For relatively recalcitrant compounds we expect these ratios to be the same for soil gas and indoor air. We also expect the ratios observed in the groundwater, soil gas, and indoor air data sets to be consistent, after proper consideration of partitioning behavior.

In this analysis, 1,1 DCE was chosen as the reference compound, simply because it was the most prevalent in the data set, and also because it was thought to be highly unlikely that there would be other sources of 1,1 DCE in the buildings or surrounding area.

This data quality analysis approach is predicated on the assumption that natural degradation of the chlorinated compounds of interest is relatively significant in the region of interest. As will be seen below, the data sets support this hypothesis. This same approach would not be appropriate if chemical degradation was significant, unless the degradation rates were identical for all chemicals.

The results of this exercise are presented in Figures 3 - 6 and Table 1. Below these figures and table, conclusions of this exercise are briefly discussed.

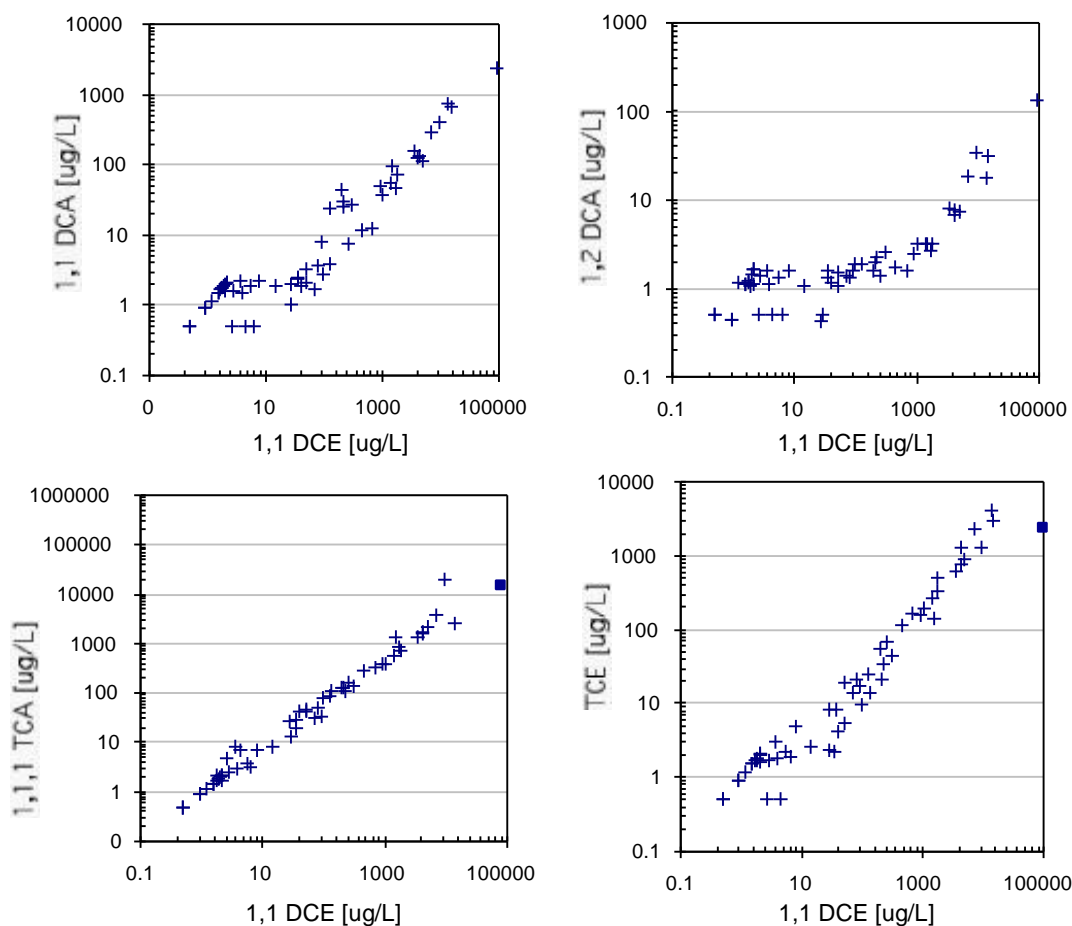


Figure 3. Results of consistency check for groundwater data set.

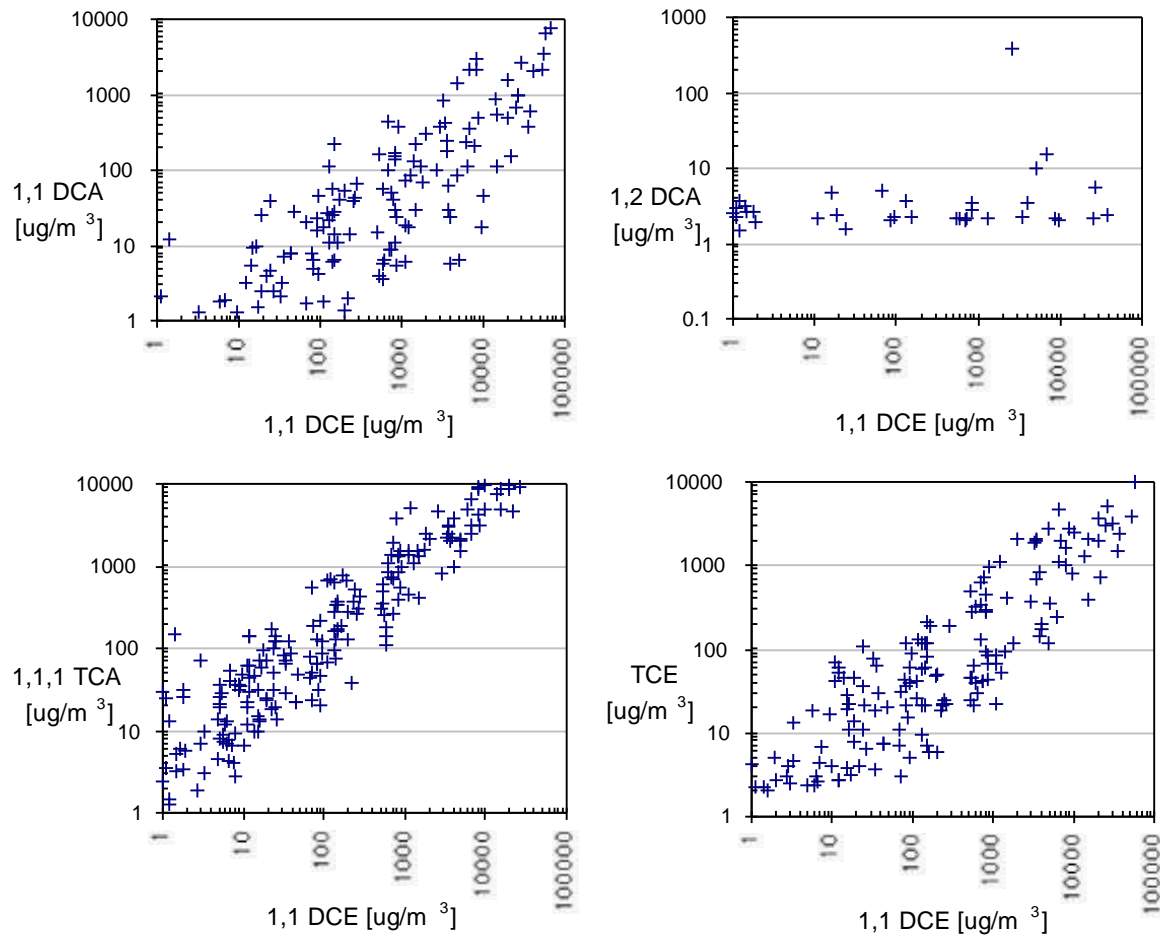


Figure 4. Results of consistency check for soil gas data set – internal consistency check.

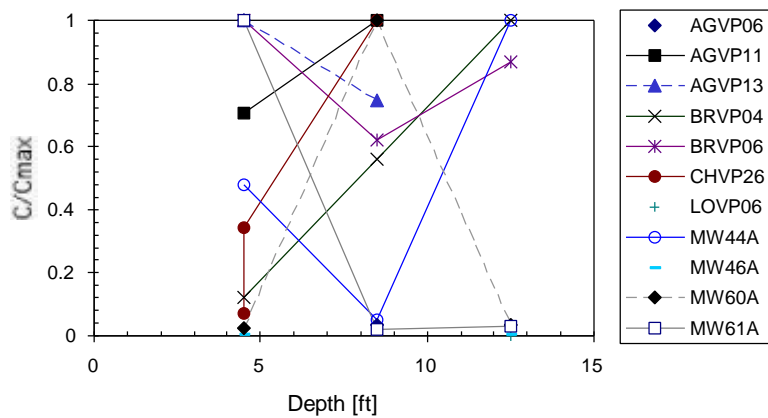


Figure 5. Results of consistency check for soil gas data set – concentration vs. depth.

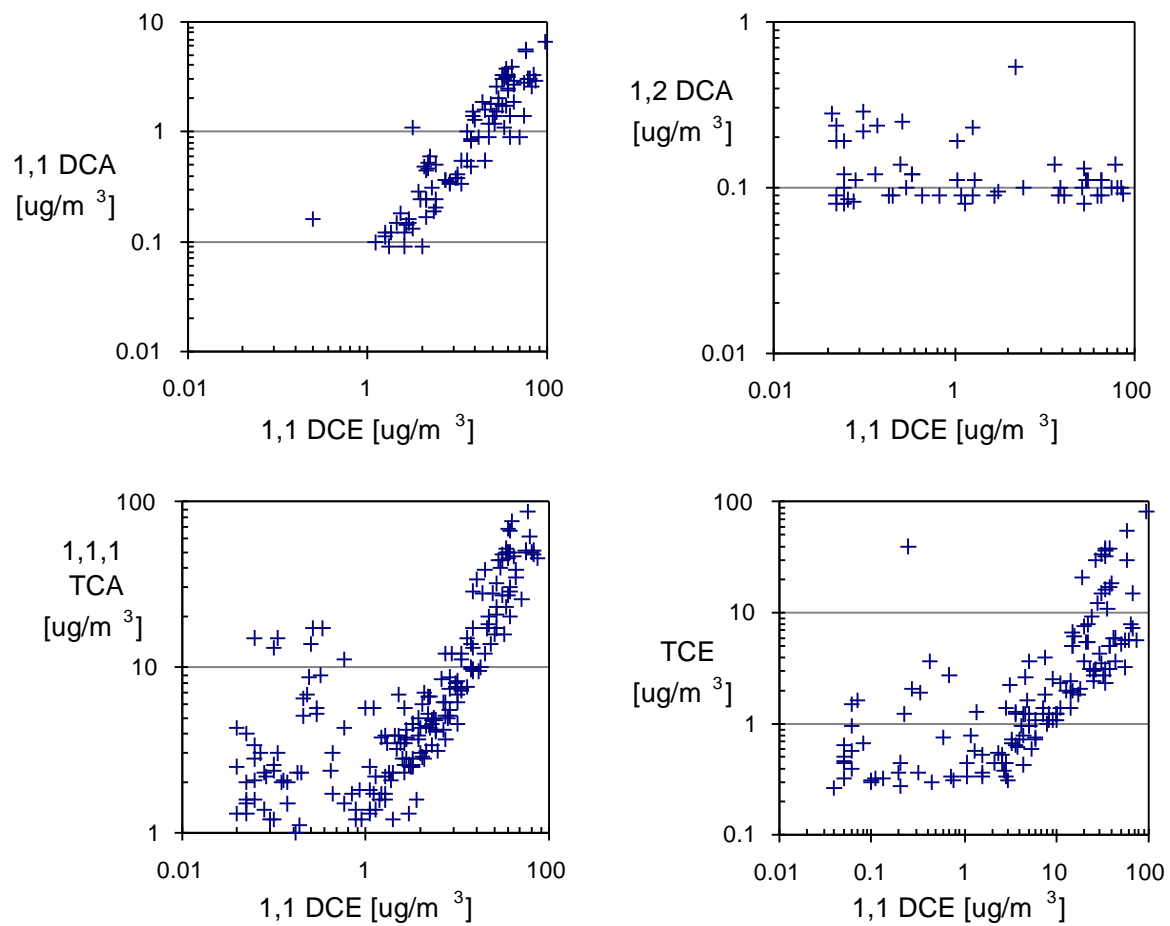


Figure 6. Results of consistency check for indoor air concentrations.

Table 1. Results of consistency checks between data sets.

	1,1 DCA	1,2 DCA	1,1,1 TCA	TCE
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average groundwater concentration/1,1 DCE	0.042	0.0017	0.59	0.19
average soil gas concentration/1,1 DCE	0.085	no correlation	1.1	0.34
average indoor air concentration/1,1 DCE	0.056	no correlation	1.0	0.19
Henry's Law Constants [(mg/L-vapor)/(mg/L-H ₂ O)]*	0.23	0.04	0.71	0.42
theoretical relationship for vapor concentrations/1,1 DCE based on groundwater relationship	0.009	0.000064	0.39	0.075

* - USEPA. 1996. Soil Screening Guidance: Technical Background Document. EPA 540/R-95/128.

The following briefly captures our observations from this data set:

- Figure 3 shows strong correlation between all chemicals and 1,1 DCE, except for 1,1 DCE and 1,2 DCA when the 1,1 DCE concentration is <10 ug/L.
- Figure 4 shows a good correlation overall between 1,1 DCA, 1,1,1 TCA, and TCE and 1,1 DCE in soil gas, but the amount of scatter in the data set is clearly much greater than for the groundwater data set. In addition, there is no correlation between 1,2 DCA and 1,1 DCE data as the 1,2 DCA data is insensitive to changes in 1,1 DCE concentrations. The relatively narrow and constant range of 1,2 DCA concentrations suggests either laboratory error or ubiquitous background sources of 1,2 DCA.
- Figure 5 shows that the soil gas data set does not behave as expected with depth. Fundamental considerations dictate that soil gas concentrations should consistently increase with depth at these soil gas points as the vapor source is groundwater; clearly this is not the case.
- Given the results of Figures 4 and 5, and experience with soil gas sampling, it is possible that the soil gas samples were compromised by leakage of atmospheric air along the sampling points and cross-contamination between samples and locations. Review of the

documents associated with the site suggest that soil gas sampling procedures were not consistent over time, and sufficient precautions were not taken to ensure against leakage and cross-contamination.

- Figure 6 is similar in many ways to Figure 4 and shows a good correlation overall between 1,1 DCA, 1,1,1 TCA, and TCE and 1,1 DCE in soil gas, but only when the 1,1 DCE concentration is $>1 \text{ ug/m}^3$. As in Figure 4, there is no correlation between 1,2 DCA and 1,1 DCE concentrations.
- Table 1 shows the ratios of groundwater, soil gas, and indoor air concentrations relative to 1,1 DCE concentrations. First, in the absence of significant degradation, it is expected that these ratios should be the same for soil gas and indoor air samples. As can be seen this is the case, to within a factor of about two. Next, ratios of chemicals in groundwater should be comparable to those in soil gas and indoor air, once corrections are made for partitioning. For example, it is expected that:

$$\left[\frac{C_{\text{indoor}}(1,1 \text{ DCA})}{C_{\text{indoor}}(1,1 \text{ DCE})} \right] = \left[\frac{C_{\text{groundwater}}(1,1 \text{ DCA})}{C_{\text{groundwater}}(1,1 \text{ DCE})} \right] \left[\frac{H(1,1 \text{ DCA})}{H(1,1 \text{ DCE})} \right]$$

where $H(1,1, \text{DCA})$ denotes the Henry's Law Constant for 1,1 DCA. The theoretical expectations, are also given in Table 1. As can be seen, agreement (to within a factor of about three to five) is reasonable for 1,1,1 TCA and TCE. The 1,2 DCA analysis suggests that 1,2 DCA should not even be detected in indoor air or soil gas, which perhaps explains the lack of correlation with 1,1 DCE concentrations shown in Figures 4 and 6. The largest discrepancy here is with the 1,1 DCA data, which shows an order-of-magnitude disagreement between theory and actual data. As discussed below in Section 4.0, this data suggests a potential systematic laboratory analysis error, where concentrations are reported to be about an order-of-magnitude different from actual values.

Based on this data quality analysis, the following rules were used to filter the initial database to create one that could be used for the empirical assessment discussed in the next section:

- Use of the groundwater data set was restricted to groundwater samples with 1,1 DCE >10 ug/L (based on the results shown in Figure 3)
- The soil gas data set was not used (based on the results shown in Figure 5).
- Use of the indoor air data set was restricted to 1,1 DCA, 1,1 DCE, 1,1,1 TCA, and TCE, and also to samples for which 1,1 DCE > 1 ug/m³ (based on the results in Figure 6).
- The 1,1 DCA data was retained in the data base, but it was flagged to indicate that data quality is suspect (based on the results in Table 1).

Upon reflection on the impact of this filtering on the database, one can see that the remaining data is now biased towards the higher concentrations in the original data sets, which seems appropriate if one considers that many sources of error (e.g., sample carry-over, lab cross-contamination, etc.) are less likely to be a problem at higher concentrations. Thus, it is reasonable that this is the data set that one would have high confidence in.

4.0 Derivation of Empirical Subsurface –to- Indoor Air Attenuation Factors from Field Data

Johnson and Ettinger (1991) define the “attenuation factor” α to be the ratio of the indoor air concentration of some chemical i $C_{\text{indoor}}(i)$ divided by the equilibrium soil gas concentration $C_{\text{source}}^*(i)$ of that chemical at the source. For the case of steady groundwater sources, the definition of α is given by:

$$\alpha = \left[\frac{C_{\text{indoor}}(i)}{C_{\text{source}}^*(i)} \right] = \left[\frac{C_{\text{indoor}}(i)}{H(i) C_{\text{groundwater}}(i)} \right]$$

where $C_{\text{groundwater}(i)}$ and $H(i)$ denote the groundwater concentration and Henry's Law Constant for the chemical i of interest.

Thus, calculation of attenuation factors (α) is straight-forward when one has groundwater and indoor air concentrations at the same location, and both are relatively stable with time.

Unfortunately, the CDOT-MTL data set does not contain synoptic samplings; that is,

groundwater samples and indoor air samples were collected at different times, locations, and with different frequencies (i.e., groundwater wells are not located beneath the buildings).

However, review of the data showed relatively stable groundwater concentrations with time and variations in indoor air samples were less than an order of magnitude (and typically less than a factor of three). Therefore, the following approach was adopted:

- Groundwater concentrations in all wells were averaged with time over a three-year period. That data was then contoured and concentrations beneath individual apartments were assigned based on those contour plots.
- Indoor air data was used as is, and attenuation factors were calculated for each sampling event.

Results of this analysis are given in Figure 7 and Table 2. In Figure 7, the attenuation factors are plotted vs. groundwater concentration for each chemical. In addition, the data are presented by apartment building, apartment, and sampling event. All apartments in the same building are assigned the same symbol and these are plotted at the average value for that apartment; the error bars then define the range of the maximum and minimum α values for that apartment. In almost all cases, the α values lie within the 10^{-6} to 10^{-4} range. In the case of building AGA, some α values are $>10^{-4}$, but this is possibly an artifact of the calculation method as building AGA lies across a steeply contoured area where concentrations change by an order of magnitude (see Figure 1).

Figure 7 also shows that attenuation factors for 1,1 DCE, 1,1,1 TCA, and TCE are relatively consistent. The ranges and average α values are very similar as is expected from theory because the relevant steady-state transport parameters (i.e., diffusion coefficient) are very similar for most chemicals and partitioning parameter differences are already corrected for in the way that α is calculated. The α values for 1,1 DCA, however, are an order-of-magnitude greater than for the other three chemicals. Given the relative consistency between attenuation factors for 1,1 DCE, 1,1,1 TCA, and TCE, and the results of Table 1, we hypothesize that the 1,1 DCA concentrations in either soil gas or groundwater were subject to a systematic error causing the reported 1,1 DCA α values to be about an order-of-magnitude greater than actual values.

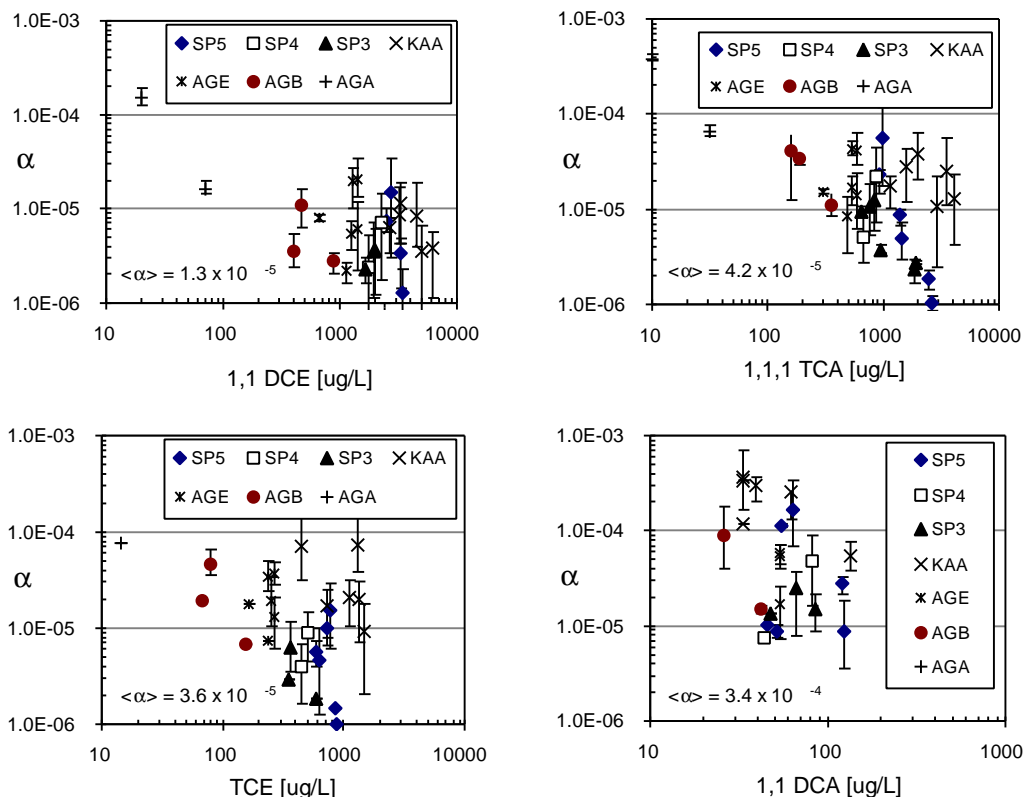


Figure 7. Subsurface-to-Indoor Air attenuation factors (α) calculated using the CDOT-MTL data sets. Symbols are plotted at the average value for a given apartment, and all apartments in the same building are assigned the same symbol. Error bars define the maximum and minimum values for each apartment.

Table 2 summarizes the results by chemical. As can be seen, the average α values by chemical for 1,1,1 TCA, 1,1 DCE, and TCE are quite similar, while the average α value for 1,1 DCA is one order-of-magnitude greater. For reference, the 90th percentile values and geometric means of the α values are also given. These are also useful quantities as the arithmetic average is inherently biased towards the larger values when the numbers vary by an order-of-magnitude or greater, and therefore can sometimes be misleading. The overall average for all apartments and chemicals (excluding 1,1 DCA) is 3×10^{-5} .

Table 2 Summary of empirical results from the analysis of the CDOT-MTL site data.

Chemical [# of data points]	1,1,1 TCA [145]	1,1 DCE [145]	TCE [111]	1,1 DCA* [90]
Average α	4.2×10^{-5}	1.3×10^{-5}	3.6×10^{-5}	3.4×10^{-4}
90th Percentile α	6.6×10^{-5}	2.0×10^{-5}	7.0×10^{-5}	3.4×10^{-4}
Geometric Mean α	1.7×10^{-5}	4.8×10^{-6}	1.4×10^{-5}	6.2×10^{-5}
Overall Average α (1,1,1 TCA, 1,1 DCE, TCE data only): 3×10^{-5}				

* - note, this data set is suspected of containing a systematic error

At this point it is worthwhile mentioning that our calculation approach may have an inherent bias towards calculating α values from the data that are higher or lower than actual values. This is because we use groundwater concentrations taken from typical groundwater wells screened across the water table and deeper. Vertical groundwater concentration profiles are not available, so the relationship between the reported groundwater concentrations and the concentration at the water table interface is unknown. However, given the available information for this site, it is reasonable to hypothesize that if a bias is present, it is towards the calculation of lower (more conservative; less attenuation) α values because concentrations at the water table interface are not expected to be lower than the groundwater concentrations reported for groundwater samples.

4.0 Comparison of Empirically-Derived Attenuation Factor with Estimates Generated Using the Johnson and Ettinger (1991) Model

Screening level algorithms for the vapor intrusion pathway couple source zone partitioning, vadose zone transport, building foundation transport, and enclosed-space mixing algorithms. The resulting algorithms then depend on parameters related to soil, chemical, and building characteristics. ASTM (1995), USEPA (1996), and some state regulatory agencies have used the Johnson and Ettinger (1991) algorithm to relate the estimated indoor vapor concentration C_{indoor} [mg/m³] to the source zone vapor concentration C_{source} [mg/m³]:

$$\alpha = \frac{\left[\frac{D_T^{\text{eff}} A_B}{Q_B L_T} \right] \exp\left(\frac{Q_{\text{soil}} L_{\text{crack}}}{D_{\text{crack}}^{\text{eff}} \eta A_B} \right)}{\exp\left(\frac{Q_{\text{soil}} L_{\text{crack}}}{D_{\text{crack}}^{\text{eff}} \eta A_B} \right) + \left[\frac{D_T^{\text{eff}} A_B}{Q_B L_T} \right] + \left[\frac{D_T^{\text{eff}} A_B}{Q_{\text{soil}} L_T} \right] \left(\exp\left(\frac{Q_{\text{soil}} L_{\text{crack}}}{D_{\text{crack}}^{\text{eff}} \eta A_B} \right) - 1 \right)} \quad (1)$$

Here $\alpha = (C_{\text{indoor}}/C_{\text{source}})$ is the vapor attenuation coefficient, and:

- A_B = surface area of enclosed space in contact with soil [m²]
- $D_{\text{crack}}^{\text{eff}}$ = effective overall vapor-phase diffusion coefficient through the walls and foundation cracks [m²/d]
- D_T^{eff} = effective overall vapor-phase diffusion coefficient between the source and foundation [m²/d]
- L_{crack} = thickness of enclosed space walls and foundation [m]
- L_T = source - foundation separation [m]
- Q_B = enclosed space air exchange rate [m³/d]
- Q_{soil} = soil gas flow rate into enclosed space due to under-pressurization [m³/d]
- η = fraction of enclosed space surface area open for vapor intrusion [m²/m²]

The effective porous media overall vapor-phase diffusion coefficients are generally determined from the Millington-Quirk formulation (Millington 1959, Millington and Quirk 1961, Millington and Shearer 1971):

$$D^{\text{eff}} = D^{\text{air}} \frac{\theta_v^{3.33}}{\theta_T^2} + \left(\frac{D^{\text{H}_2\text{O}}}{H_i} \right) \frac{\theta_m^{3.33}}{\theta_T^2} \quad (2)$$

where:

H_i = Henry's Law constant [(mg/m³-vapor)/(mg/m³-H₂O)]

θ_m = volumetric moisture content [m³-H₂O/m³-soil]

θ_T = total porosity [m³-voids/m³-soil]

θ_v = volumetric vapor content [m³-vapor/m³-soil]

D^{air} = molecular diffusion coefficient in air [m²/d]

$D^{\text{H}_2\text{O}}$ = molecular diffusion coefficient in water [m²/d]

For reference, molecular diffusion coefficients in air for most petroleum fuel compounds range from 0.05 - 0.10 cm²/s (0.4 - 0.9 m²/d), molecular diffusion coefficients in water are roughly 1/10000 of molecular diffusion coefficients in air. USEPA (1996) tabulates relevant chemical properties for many chemicals of interest. Total porosity varies roughly between 0.35 and 0.45 for most soil types; in many well-drained sandy soils, $\theta_m < \theta_T / 5$, θ_m can approach $\theta_T / 2$ in clayey soils, and θ_m approaches θ_T as one moves down through the capillary fringe to groundwater.

Here we compare field-derived α values with those estimated using the Johnson and Ettinger (1991) algorithm and a reasonable range of input values for the CDOT-MTL site. Table 3 summarizes the reasonable ranges of values input to the Johnson and Ettinger algorithm as well as the calculated attenuation factors. Inputs and results are presented for lower bound, upper bound, and best α estimates as many of the inputs were not measured at this site and had to be inferred from other site data (e.g., boring logs, site maps, verbal descriptions, etc.). The lower bound estimate combines the input ranges in the way that produces the lowest α estimate; similarly, the upper bound estimate combines the input ranges in the way that produces the greatest α estimate. The best estimate represents the input set judged by the investigators to be most representative overall of site conditions. As can be seen, the estimates given in Table 3 compare well with the empirically-derived attenuation factors given in Table 2. The reasonable

range of estimates brackets the values calculated from field data, the best-estimate value is within the same order-of-magnitude as the overall average value, and it is also slightly greater than 90% of all calculated values.

Table 3. Inputs for Johnson and Ettinger model for the CDOT Site and the resulting attenuation factor α estimates (using TCE chemical properties).

Parameter	Lower Bound α Estimate	Upper Bound α Estimate	Best α Estimate
Depth to Groundwater [cm]	610	305	457
Capillary Fringe Height [cm]	50	10	20
Soil Porosity [vol/vol]	0.35	0.45	0.40
Vadose Zone Moisture Saturation [% of porosity]	0.45	0.25	0.35
Capillary Zone Moisture Saturation [% of porosity]	0.90	0.80	0.80
Q_{soil} [L/min]	1	10	10
η [area cracks/total area]	0.0005	0.005	0.001
Building Height [cm]	366	305	305
Air Exchange Rate [h^{-1}]	0.5	0.45	0.45
Basement Footprint [cm^2]	8.9×10^5	8.9×10^5	8.9×10^5
Attenuation Factor Estimate	4.8×10^{-6}	2.4×10^{-4}	8.6×10^{-5}

Use of a reasonable range of input values is useful for assessing screening-level model sensitivity to the inputs, and this information can be used to identify key field data needs. Table 4 has been constructed to help illustrate the Johnson and Ettinger (1991) model sensitivity to inputs for this case; here we start with the α value calculated for the upper-bound estimate input values and

then sequentially substitute in the values for the lower-bound estimate and observe the changes in α at each step.

Table 4. Sensitivity of the Johnson and Ettinger α estimates to sequential changes in inputs for reasonable values for the CDOT-MTL site.

Parameter Changed	Initial Upper Bound α Input Values		Upper Bound α Estimate	Result: New α Estimate*
Starting Point: Initial α Estimate Using All Upper Bound Estimate Parameters				2.4×10^{-4}
Sequential Changes				
1. Depth to Groundwater [cm]	305	changed to	610	1.9×10^{-4}
2. Capillary Fringe Height [cm]	10	changed to	50	6.0×10^{-5}
3. Soil Porosity [vol/vol]	0.45	changed to	0.35	4.3×10^{-5}
4. Vadose Zone Moisture Saturation [% of porosity]	0.25	changed to	0.45	3.5×10^{-5}
5. Capillary Zone Moisture Saturation [% of porosity]	0.80	changed to	0.90	6.4×10^{-6}
6. Q_{soil} [L/min]	10	changed to	1	6.3×10^{-6}
7. η [area cracks/total area]	0.005	changed to	0.0005	6.3×10^{-6}
8. Building Height [cm]	305	changed to	366	5.3×10^{-6}
9. Air Exchange Rate [h^{-1}]	0.45	changed to	0.5	4.8×10^{-6}
10. Basement Footprint [cm^2]	8.9×10^5	no change	8.9×10^5	4.8×10^{-6}

* - α values reflect cumulative changes in parameter values to that point. For example, the α value for parameter change #6 also includes parameter changes 1 through 5.

In this case only the changes in capillary fringe moisture content and capillary fringe height effect > 50% change in α values. With respect to the remaining parameters, changing the total porosity and vadose zone moisture content caused about 20 - 30% changes in α , and all other input changes effected less than 10% changes. These observations are typical for scenarios where groundwater plumes are the vapor source as transport across the capillary fringe is the limiting transport process. The results indicate that reasonable estimates can be obtained for problems like this, as long as reasonable estimates of the capillary fringe height and moisture content can be made. The model estimates typically only become sensitive to the other parameters when the vapor source is located in the unsaturated zone within about 1 m of the building foundation. When that is the case, model results are typically most sensitive to estimates of the soil gas convective flow rate, for reasonable ranges of all input parameter values. Sensitivity to other input parameters is similar to that shown in the example above.

5.0 Reflection and Lessons Learned

While this analysis only focuses on one site, there are number of valuable lessons that can be learned from the data quality analysis exercise and comparison of screening-level model estimates with field data-derived attenuation factors.

First, the quantitative comparison of screening level model α estimates with values calculated using the field data demonstrates that the screening level model was capable of predicting reasonable values for this site. Estimates agreed well with field data-derived values to within an order-of-magnitude, which is a reasonable expectation for a screening-level model. Use of a reasonable range of input values also helped to assess the sensitivity of the screening level model to its inputs and to identify key field data that could be use to reduce the uncertainty.

Second, this data quality analysis exercise provides insight to the challenges associated with assessment of this pathway via indoor air sampling. To draw any technically-defensible conclusions about the impacts of subsurface contaminants on indoor air at a given site, one must first have data that conclusively establishes a link between subsurface and indoor air

concentrations. The mere presence of a chemical in both the subsurface and indoor air is in general insufficient to establish that linkage, given the high potential for other above-ground and indoor sources of many volatile organic chemicals of interest. Short of adding tracers, or having chemicals for which no other sources exist, one must rely on observation of changes in indoor air concentration with changes in subsurface concentrations to establish this linkage. This can be accomplished by observing changes with time at one or more points, or by observing concentrations at different spatial locations. The former is likely to be impracticable at many sites due to characteristic transport times in the subsurface; thus, measurement in many residences overlying a wide range of concentrations is necessary.

In light of this discussion it is important to note that the CDOT-MTL site is unique in terms of the extent of available data; groundwater, soil gas, and indoor air sampling data is available for a multi-year period and over a large spatial area. It also unique in terms of the amount of money allocated for direct measurement, assessment costs are well in excess of \$1,000,000 (US). In contrast, the more typical conventional assessment by direct measurement involves one or two sampling events in a single residence.

Thus, assessing the significance of the subsurface-to-indoor air pathway via direct measurement is likely to be impracticable for most sites. We suggest that a more cost-effective and practicable approach would involve the use of site assessment data and screening-level models to identify those sites that warrant further investigation by direct measurement. Some level of site assessment data is necessary as the screening level estimates would be too uncertain without it; however, it is anticipated that the required data would not represent a significant increase in data collection relative to current practices. For example in the CDOT-MTL site, reasonable screening level model estimates were achieved using limited site assessment data (depth to groundwater, qualitative soil boring log data, and approximate building/residence characteristics).

Finally, it is important to remind the reader that: a) the conclusions and observations from this site are most applicable to other sites having relatively recalcitrant dissolved groundwater contaminants; b) it is expected that the magnitude of attenuation may be more substantial at sites

where the contaminants of concern are naturally more readily degradable; c) it is also expected that the magnitude of attenuation may be less where the contaminant vapor source is located in the vadose zone; and d) the data supports the validity of the Johnson and Ettinger (1991) for cases where degradation is expected to be insignificant, but not for situations involving more readily degradable compounds. Modifications to that model to include degradation terms have been given in API (1998), and development of other refinements are in progress (Johnson et al. 2000).

7.0 References

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